Received: 31 July 2023 | Accepted: 29 January 2024 | Published online: 7 March 2024

DOI: 10.1002/saj2.20648

Soil Science Society of America Journal

ORIGINAL ARTICLE

Agricultural Soil and Food Systems

Effectiveness of wood ash and paper sludge as liming and nutrient sources for annual ryegrass grown in podzolic soils of Newfoundland

Bilal Javed[1] | **Yeukai Katanda**[1] | **Muhammad Nadeem**[2] | **Thilini Wickremasinghe**[1] | **Muhammad M. Farhain**[1] | **Raymond Thomas**[3] | **Lakshman Galagedara**[1] | **Xiaobin Guo**[2] | **Mumtaz Cheema**[1]

[1]School of Science and the Environment, Memorial University of Newfoundland, 20 University Drive, Corner Brook, Newfoundland and Labrador A2H 5G4, Canada

[2]Department of Fisheries, Forestry and Agriculture, Government of Newfoundland and Labrador, Corner Brook, Newfoundland and Labrador, Canada

[3]Biotron Experimental Climate Change Research Centre, Department of Biology, Western University, London, Ontario, Canada

Correspondence
Mumtaz Cheema, School of Science and the Environment, Memorial University of Newfoundland, 20 University Drive, Corner Brook, NL A2H 5G4, Canada.
Email: macheema@mun.ca

Assigned to Associate Editor Alex Woodley.

Funding information
Agricultural Clean Technology Program; Atlantic Canada Opportunities Agency (ACOA); Department of Tourism, Culture, Industry and Innovation; Department of Fisheries, Forestry and Agriculture; Corner Brook Paper Mills Ltd.; Memorial University of Newfoundland

Abstract

The acidic soils of western Newfoundland require liming for successful production of most crops. Locally sourced paper mill waste wood ash (WA) and paper sludge (SL) have potential as cheaper alternatives to limestone (LIME). Two greenhouse experiments evaluated WA and SL as liming and soil conditioning amendments for annual ryegrass (*Lolium multiflorum*) production. At 55 days after seeding, soil pH in WA (6.2 and 6.3) and wood ash and paper sludge (WASL) (6.0 and 6.3) were not different from that in LIME (6.0 and 6.5) for Experiments 1 and 2, respectively. However, pH in SL was 0.4 and 0.3 points lower than in LIME. Compared to LIME, WA, SL, and WASL produced 31%–52% and 57%–74% greater biomass yield in Experiments 1 and 2, respectively. N uptake was greater in WA (60 and 129 kg N ha^{-1}) and WASL (51 and 97 kg N ha^{-1}) compared to LIME (40 and 85 kg N ha^{-1}), in Experiments 1 and 2, respectively. SL did not differ from LIME in Experiment 1, but reduced N uptake by 57% in Experiment 2. The results show significant potential of WA as an alternative amendment for liming and yield improvement of annual ryegrass grown in NL podzolic soils. However, SL has limited potential due to the risk of increasing N immobilization and residual soil mineral N when growing conditions are limiting. Combining SL with WA or biochar seemed to alleviate these risks. Overall, the adoption of these amendments for field production systems warrants serious consideration, following supplemental field studies to determine optimal application rates and timing.

Abbreviations: AM, liming amendment; BC, biochar; CBPPL, Corner Brook Pulp and Paper Ltd.; CCE, calcium carbonate equivalent; DAS, days after seeding; DMY, dry matter yield; LIME, limestone; NL, Newfoundland and Labrador; SL, paper sludge; WA, wood ash; WASL, wood ash and paper sludge; WFPS, water-filled pore space.

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.
© 2024 The Authors. *Soil Science Society of America Journal* published by Wiley Periodicals LLC on behalf of Soil Science Society of America.

1 | INTRODUCTION

North American pulp and paper industry generates significant volumes of wood ash (WA) and paper sludge (SL) as waste by-products (Cherian & Siddiqua, 2019). Landfill disposal of paper mill waste is costly due to rising costs for tipping fees and shipping (Gagnon & Ziadi, 2023). The Corner Brook Pulp and Paper Ltd. (CBPPL) mill spends \$69 Mg^{-1} on dump waste byproducts at landfill site located 44.5 km away from the production site. Moreover, these costs are expected to rise further due to the consolidation of landfill sites at the provincial level and the need to transport these wastes over greater distances (Barrett & Vodden, 2023). To reduce disposal costs and potential environmental pollution, WA and SL can be used as valuable alternative sources of nutrients for crop production (Camberato et al., 2006; Quaye et al., 2011). Both materials contain various essential nutrients that are beneficial for plant growth, including nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and micronutrients (Norrie & Fierro, 2020; Rodríguez et al., 2019). Paper mill waste undergoes an oxidation process during treatment, resulting in SL with plant-available nutrients.

Sustainable management of large volumes of paper mill wastes in an economically viable, socially acceptable, and environmentally sound manner is one of the most critical challenges faced by the industry across the globe (Cherian & Siddiqua, 2019; Likon & Trebe, 2012; Simão et al., 2018). One such sustainable management option is the recycling of WA and SL as liming and nutrient sources in crop production (Kinnula et al., 2020; Medaiyese et al., 2023; Paramisparam et al., 2021). The application of WA has been reported to increase nutrient uptake and yield of *Sorghum bicolor* L. (Abbasi et al., 2013) and *Lolium perenne* L. (Ochecova et al., 2014). Ríos et al. (2012) reported that SL as a soil amendment increased soil organic matter and P content, consequently increasing the biomass of *Lolium perenne* L. The agricultural benefits of WA and SL therefore extend beyond their liming potential, including improvements in soil health and plant nutrient supply. However, WA and SL have not been evaluated as liming and nutrient sources in Newfoundland and Labrador (NL).

NL soils are predominantly podzolic and cover 60% of the province's land area, and current expansion of agriculture in NL increases opportunities and the potential for WA as an organic soil amendment and as a source of plant nutrients for both field and greenhouse crop production. Podzols are darker alluvial soils having high levels of aluminum (Al^{3+}) and iron (Fe^{2+}) ions and organic matter in the B horizon (Saha et al., 2020). Dissolved Al^{3+} in these soils could be toxic and may inhibit root growth by damaging the root apical cells, affecting the plant's uptake of nutrients and water, resulting in poor yield (Kopittke et al., 2015; Yamamoto, 2019). In addition, podzolic soils have high percentage of clay minerals containing kaolinite and iron oxides, which can fix phosphorous (P) and make it unavailable for plant uptake. Low pH, excessive Al^{3+}, and unavailability of P are the main causes of low agriculture production in podzols (Zheng, 2010). Raising soil pH, fertility, and health are key factors to enhance crop productivity in podzolic soils.

Core Ideas

- The podzolic soils of Newfoundland have low pH and fertility, hence require liming.
- Locally sourced wastes, such as paper mill wood ash (WA) and sludge (SL), could be used as liming and nutrient sources.
- WA was equivalent to limestone (LIME) in improving and sustaining optimal soil pH.
- WA produced 52% and 74% greater annual ryegrass yield than conventional LIME application in podzolic soils.

Due to low fertility and high acidity, NL soils require regular applications of lime and fertilizers to supplement elements necessary for plant growth (Kedir et al., 2021). There can be up to 40% reduction in nutrient uptake and production efficiency in crops when the pH level is below 5.9. At pH below 5.0 (very acidic), Al, Fe, and manganese (Mn) become more available, which are toxic to crops. Excess Al^{3+} can restrict root growth and function in crops (Hajiboland et al., 2023). Previous chemical analyses of WA samples collected from the Wild Cove, NL (paper mill landfill site) showed a very high pH of 12.7, total carbon of 58%, total P and K of 1.26%, and 1.42%, respectively. This suggests that WA could be used as a liming material and plant nutrient source for agricultural soils on the west coast of NL; however, the safety and feasibility of such an application have yet to be proven. The effectiveness of WA and SL as liming agents varies depending on carbonate and bicarbonate contents, liming potential, application rates, the initial and target pH of the receiving soil, and solubility compared to limestone (LIME) (Royer-Tardif et al., 2019; Yang et al., 2018). The neutralizing potentials of WA and SL can range between 8%–90% and 12%–60%, respectively (Kar et al., 2014). Moreover, WA and SL contain organic matter and essential nutrients for plant growth, such as nitrogen (N), calcium (Ca), magnesium (Mg), potassium (K), and phosphorus (P) (Cruz et al., 2023).

The major factor limiting the adoption of paper mill waste for crop production are concerns regarding organic and heavy metal contaminants (Hanson et al., 2023). Heavy metals are common in mill waste due to fossil fuels used during the combustion of feedstock in boilers; these trace metals may potentially leach down from fields or landfill sites and pollute

groundwater sources (Pazalja et al., 2021). Biochar (a carbon-rich product produced from pyrolysis of organic residues) can reduce the potential risks of heavy metal toxicity in mill waste products (Elkhlifi et al., 2023). Additionally, biochar (BC) can also improve soil physicochemical and biological properties (Farhain et al., 2022; Medaiyese et al., 2023), reduce nutrient leaching (Cairns et al., 2022), and reduce greenhouse gas emissions (Mosa et al., 2023).

This study aims to evaluate the potential for utilizing paper mill waste WA and SL alone and in combination with BC for liming and soil conditioning to support the production of annual ryegrass. We hypothesize that these amendments can sufficiently raise and maintain soil pH, as well as promote biomass yield and N uptake, reducing residual mineral N that is prone to leaching and denitrification losses. Using amendments with greater soil conditioning capacity than LIME would not only benefit crop production potential but also the local paper mill and broader provincial economy. The addition of BC to paper mill waste WA and SL, though primarily done to curb the risks of heavy metal pollution, could also improve soil quality and crop production potential.

2 | MATERIALS AND METHODS

2.1 | Soil and amendment preparation and characterization

The greenhouse experiments were conducted at Wooddale Provincial Tree Nursery, Grand Falls-Windsor (49.0249° N, 55.5488° W), NL. Soil was collected from the 0- to 20-cm depth of virgin fields (newly cleared forest land) and passed through a 4-mm sieve before air-drying. CBPPL utilizes black spruce (*Picea mariana*) and balsam fir (*Abies balsamea*) as feedstock for burning in the power generation process using crude oil. Therefore, to capture variability in waste by-products, 30 grab samples of WA (a mixture of bottom and fly ash) and SL were obtained from CBPPL twice daily (10 a.m. and 3 p.m.) for 15 days and mixed to make composite samples. The homogenized composite samples were air-dried, ground on a Wiley Mill (A.H. Thomas Co.) and passed through a 2-mm sieve prior to analysis and application. The agricultural LIME used in this study was a mixture of calcite ($CaCO_3$) and dolomite [$CaMg(CO_3)_2$], purchased from NCL Contractors (Ltd.). Soil and amendments were analyzed for basic properties (Table 1).

Soil pH and electrical conductivity were analyzed using a 1:2 (w/v) extract at room temperature (Hendershot et al., 1993). The pH of WA and SL was determined from saturated pastes. Exchangeable bases (K, Mg, Ca, and Na) were determined using an inductively coupled plasma mass spectrometry following extraction with 1.0 N ammonium acetate solution (Simard, 1993). Total C and N were measured by dry combustion using a LECO CN 828 dry combustion analyzer (LECO Corporation). Mineral N ($NO_3^- + NH_4^+$) was extracted using 2 M KCl and analyzed by flow injection (USEPA, 1993). The calcium carbonate equivalent (CCE) of WA and SL was determined by acid digestion using HCl (Muse & Mitchell, 1995). The BC used in this study was produced from yellow pine wood pyrolyzed at 500°C for 30 min (supplied by AirTerra Inc.). Electron microscopy images of the BC are presented in Figure 1, and selected properties are shown in Table 2.

2.2 | Experimental setup

Two greenhouse experiments, comprised of eight treatments, were arranged in a 4 × 2 factorial randomized complete block design (RCBD) and replicated three times. The treatments were different combinations of four liming materials (LIME, WA, SL, and a 4:1 wood ash and paper sludge [WASL] mixture) and two BC levels (0 and 20 Mg ha^{-1}). Amendment application rates were based on the amounts needed to attain a target pH of 6.3. To determine the optimal rates needed to reach the target pH, theoretical rates based on the CCE and lime requirement of the soil as recommended by the provincial soil laboratory were calculated for WA and SL (Equation 1) as follows:

$$\text{Application rate} = \frac{\text{Area} \times \text{LR}}{\text{CCE} \times (100 - \text{Percentage moisture content})} \quad (1)$$

where CCE is the calcium carbonate equivalence and LR is the lime requirement (Mg ha^{-1}).

Soil was mixed with amendments corresponding to 100%, 70%, 50%, and 25% of the theoretical rates. Soil pH was measured once every 24 h until a constant pH was achieved (7 days) to determine amendment rates that produced the target pH. For Experiments 1 and 2, optimal rates of LIME, WA, and SL were 7.1, 17.25, and 55 Mg ha^{-1}, and 8.1, 20, and 94 Mg ha^{-1}. Biochar was added at 20 Mg ha^{-1} (Moragues-Saitua et al., 2017), while WASL and WASLBC were formulated as a 4:1 mixture of WA and SL based on weight (13.8 + 11 and 16 + 18.8 Mg ha^{-1} for Experiments 1 and 2, respectively). Respective quantities of amendments for each treatment were thoroughly mixed with 2 kg of air-dried soil and lightly packed in 15-cm (diameter) pots. In Experiment 1, each pot was watered to 55% water-filled pore space (WFPS) with tap water and left for 7 days for soil stabilization before seeding. For Experiment 2, pots were watered with 55% WFPS, and seeding could not proceed because of a 90 days lockdown due to the COVID-19 pandemic. Upon greenhouse reopening, the soil in each pot was subsampled for pH analysis, and additional amendments were added as needed to restore the target pH of 6.3. Differences in amendment rates

TABLE 1 Selected properties of soil, wood ash, and paper sludge used in the current study.

Parameters	Soil		Wood ash	Paper sludge	CCME limits
	Experiment 1	Experiment 2			
pH	5.7	5.2	12.6	8.2	–
Soil texture	Sandy loam	Silt loam	–	–	–
Electrical conductivity (dS m^{-1})	0.04	0.03	0.009	0.0003	–
Organic matter (%)	2.7	4.5	–	–	–
Potassium, extractable (mg kg^{-1})	29	54	2.42	1.36	–
Calcium, extractable (g kg^{-1})	0.116	0.06	23.6	5.44	–
Ammonium-NH_4^+ (mg kg^{-1})	4.79	3.18	0.75	876	–
Nitrate-NO_3^- (mg kg^{-1})	0.61	5.21	5.09	2	–
Total carbon (g kg^{-1})	–	–	50.9	401	–
CN ratio	–	–	16.66	38.55	–
Total nitrogen (g kg^{-1})	0.5	0.8	0.30	1.04	–
Organic carbon (g kg^{-1})	12.9	18	34.5	399	–
CCE	–	–	10.4	12.9	–
Arsenic (mg kg^{-1})	8.8	10	2.5	2.1	41
Cadmium (mg kg^{-1})	0.09	0.061	1.3	3.1	15
Chromium (mg kg^{-1})	36	31	130	55	1000
Cobalt (mg kg^{-1})	8.2	8.2	14	5.1	150
Copper (mg kg^{-1})	13	13	190	94	1500
Lead (mg kg^{-1})	7.9	8.7	20	35	300
Mercury (mg kg^{-1})	0.05	0.63	0.04	0.2	4
Molybdenum (mg kg^{-1})	0.42	0.44	16	6.3	20
Nickel (mg kg^{-1})	19	16	88	42	180
Selenium (mg kg^{-1})	0.36	0.46	0.17	0.44	25
Zinc (mg kg^{-1})	31	18	670	890	1850

Abbreviations: CCE, calcium carbonate equivalent; CCME, Canadian Council of Ministers of the Environment (2012).

TABLE 2 Physicochemical properties of biochar used in study.

Parameter	Value
pH	9.0
Electrical conductivity (dS m^{-1})	5.2
Water-holding capacity (mL H_2O 100 g^{-1} drychar)	74.9
Cation exchange capacity (cmol kg^{-1})	11.1
Total C (%)	86.8
Total N (mg kg^{-1})	400
Total ash (g kg^{-1})	71
Recalcitrant C (g kg^{-1})	760
Neutralizing value (g kg^{-1} as $CaCO_3$)	490
Bulk density (Mg m^{-3})	0.19
Void space (% v/v)	87.5

between the two experiments were due to differences in soil properties (Table 1), as well as the additional time between amendment application and seeding of Experiment 2.

Pots were watered to 55% WFPS and left for 7 days to stabilize before seeding. In both experiments, 20 seeds of annual ryegrass (*Lolium multiflorum*) were planted at 1-cm depth (Park et al., 2012). Fertilizer rates were determined based on crop requirements and nutritional status of the soil, as recommended by the provincial soil fertility specialist. Accounting for nutrients available in added amendments, all pots received supplemental urea, triple superphosphate, and murate of potash to respectively supply recommended N, P, and K for annual ryegrass. Additional fertilizers added were 150 kg N, 87 kg P, and 149 kg K ha^{-1} for Experiment 1, and 180 kg N, 52 kg P, and 128 kg K ha^{-1} for Experiment 2. The pots were organized on separate tables based on replicate/block. Throughout the study, watering was done once per week to replenish moisture to 55% WFPS, allowing <10% depletion between watering events. The selected WFPS was considered the optimal moisture content for plant growth and soil microbial activity in this study and was determined as the proportion of total pore volume based on oven-dry weight of soil and bulk density (Katanda, 2022; Linn & Doran, 1984). At 14 days after seeding (DAS), thinning was done to reduce the number of plants to 16 per pot. The greenhouse growth conditions for both experiments are shown in Figure 2 below. In Experiment 1, temperature was 21 ± 2°C for ~16 h

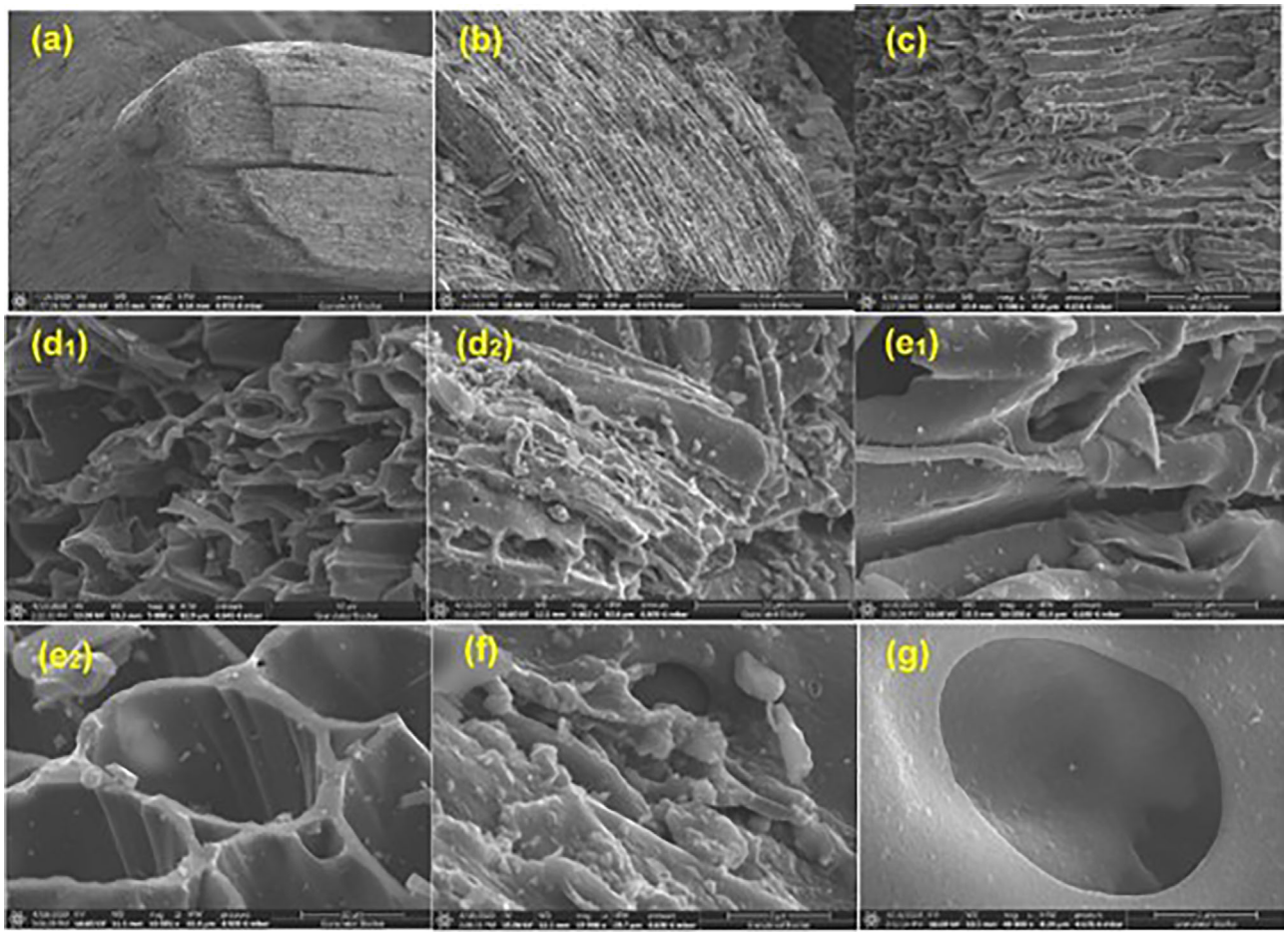


FIGURE 1 Scanning electron microscopy images of yellow pine wood (*Pinus* spp.) biochar at different magnifications and scales: (a) 100× mag—1-mm scale; (b) 500× mag—300-μm scale; (c) 1000× mag—100-μm scale; (d1) 5000× mag—30-μm scale; (d2) 5000× mag—30-μm scale; (e1) 10,000× mag—10-μm scale; (e2) 10,001× mag—10-μm scale; (f) 19,998× mag—5-μm scale; (g) 49,999× mag—2-μm scale.

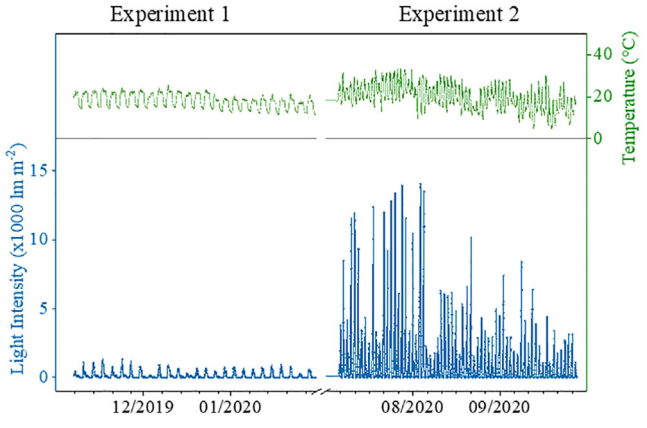


FIGURE 2 Temperature and light intensity in greenhouse during experiments to assess liming potential of wood ash and sludge.

during the day and 15 ± 2°C for ~8 h at night. The light intensity was low due to gloomy winter conditions (low natural light) and varied between 42 and 786 lux, while the humidity ranged from 38% to 54% throughout the experiment. For Experiment 2, temperature was 25 ± 2°C for 16 h during the day and 13 ± 1°C for 8 h at night. Light intensity ranged from 369 to 5366 lux, whereas humidity ranged from 55% to 88%.

2.3 | Sampling and analyses

At 55 DAS, annual ryegrass shoots were harvested by clipping at the soil surface. Samples were bagged and oven-dried at 65°C for 72 h. The dry matter yield (DMY) of harvested samples was calculated as shown in Equations (2) and (3).

$$\text{Dry matter}(\%) = \left(\frac{\text{Fresh weight} - \text{dry weight}}{\text{fresh weight}}\right) \times 100 \quad (2)$$

$$\text{Dry matter yield (Mg/ha)} = \text{DM}\ (\%) \times \left(\frac{10,000}{\text{pot surface area}}\right) \times \text{sample weight} \quad (3)$$

The oven-dried plant samples were pulverized using a ball-mill grinder (Retsch Cryomill) and thoroughly homogenized in preparation for analyses of N content. The soil from each pot was thoroughly mixed, and roots were removed before collecting a 500 g subsample for laboratory analyses. A 50 g sample of moist soil was sieved with a 2-mm mesh, stored at 4°C, and extracted for analysis of residual soil mineral N (NH_4^+ and NO_3^-) within 72 h of sampling. The rest of the soil was sieved with a 2-mm mesh, air-dried, and ground using a mortar and pestle prior to analysis for total C and N (Bertsch & Ostinelli, 2019). Residual soil nitrogen (NH_4^+ + NO_3^-) after crop harvest was determined by extraction of 5 g sieved (<2 mm) field-moist soil with 50 mL of 2 M KCl, followed by flow injection analysis (Maynard & Kalra, 2008) using a continuous flow analyzer (Bran Luebbe AA3, Seal Analytical Inc.). Soil pH was determined from a 1:2 (w/v) soil/water suspension using a handheld pH meter (Bluelab Combo Meter). Total C and N in soil samples were measured by dry combustion using a LECO TruSpec CN autoanalyzer (LECO Corporation) (Bertsch & Ostinelli, 2019).

2.4 | Statistical analysis

Two-way analysis of variances were performed to determine the effects of liming amendments (AMs) and BC on soil pH, DMY of annual ryegrass, and residual soil nitrogen concentration using the Statistix 10 software package (Analytical Software). The normality of residuals was checked using the Shapiro–Wilk test. Comparisons of treatment least-square mean estimates were done using Fisher's least significant difference test at the 5% significance level for all pairwise comparisons. Graphs were prepared using OriginPro 2021 (OriginLab Corporation).

3 | RESULTS

3.1 | Plant nitrogen uptake

There was a significant AM effect on N uptake in both experiments (Table 3). Compared to LIME, WA and WASL significantly increased N uptake in Experiment 1 by 48% and 26%, respectively. There was no significant difference in N uptake between LIME and SL. Nitrogen uptake was significantly higher in WA and WASL than in SL. Overall, BC application did not significantly affect N uptake in this experiment. Similarly, in Experiment 2, WA and WASL significantly increased N uptake by 52% and 14%, respectively, whereas SL significantly reduced N uptake by 57%. There was a significant BC effect on N uptake; for all AMs, BC addition significantly reduced N uptake by 12% (Table 3).

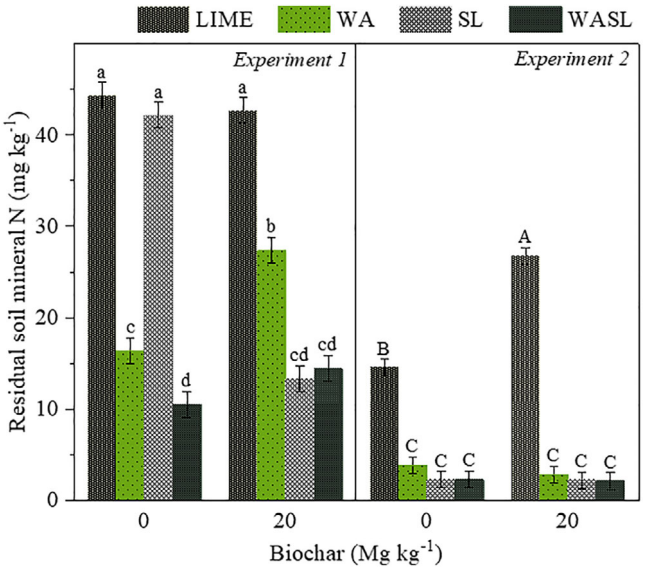


FIGURE 3 Residual mineral nitrogen in soil at 55 days after seeding annual ryegrass. LIME, limestone; SL, paper sludge; WA, wood ash; WASL, wood ash and paper sludge. Bar showing different letters indicate significant differences among treatment means (Fisher's LSD test at $p < 0.05$). Lower case and upper case letters indicate significance in Experiment 1 and Experiment 2 respectively.

3.2 | Dry matter yield

In both experiments, there was a significant AM effect on annual ryegrass DMY (Table 3). Regardless of BC application level, WA, SL, and WASL, respectively, produced 52%, 31%, and 41% higher DMY compared to LIME in Experiment 1, and 74%, 57%, and 74% higher in Experiment 2. In both experiments, there were no significant differences among WA, SL, and WASL. Overall, BC did not significantly affect annual ryegrass DMY in both experiments.

3.3 | Soil pH

In both experiments, there were significant amendment effects on soil pH at 55 DAS (Table 4). The soil pH in WA and WASL was not different from that in LIME. However, pH in SL was 0.4 and 0.3 points lower than in LIME in Experiments 1 and 2, respectively.

3.4 | Residual soil nitrogen and soil CN ratio

There was a significant AM × BC effect on residual soil N (Table 4). In both experiments, residual soil mineral N was highest in LIME treatments, with or without BC (Figure 3). In Experiment 1, the addition of BC significantly increased soil mineral N in WA, but reduced it in SL. Conversely, adding BC did not significantly affect soil mineral N in

TABLE 3 Effects of soil amendments on plant N uptake and annual ryegrass yield under greenhouse conditions.

	Experiment 1		Experiment 2	
Source of variation	**N uptake (kg ha^{-1})**	**DMY (Mg ha^{-1})**	**N uptake (kg ha^{-1})**	**DMY (Mg ha^{-1})**
Amendment (AM)				
LIME	40.4c	1.16b	85.1b	2.3b
WA	59.9a	1.76a	129a	4.0a
SL	40.5c	1.52a	36.5c	3.6a
WASL	51.1b	1.64a	96.9b	4.0a
Biochar (BC)				
0 Mg ha^{-1}	49.8	1.60	92.2a	3.59
20 Mg ha^{-1}	46.1	1.44	81.5b	3.35
		***p*-value**		
AM	<0.001	<0.001	<0.001	<0.001
BC	0.19	0.06	0.003	0.13
AM × BC	0.17	0.29	0.28	0.58

Note: Letters denoting pairwise comparisons in the table represents the reuslts of LSD tests. Different letters signify statistically significant differnces at $p < 0.05$.
Abbreviations: DMY, dry matter yield; LIME, limestone; SL, paper sludge; WA, wood ash; WASL, WA + SL.

TABLE 4 Effects of liming amendments and biochar on soil pH, residual soil nitrogen, and soil CN ratio in annual ryegrass grown under greenhouse conditions.

	Experiment 1			Experiment 2		
Source of Variation	**Soil pH**	**Residual soil mineral N (mg kg^{-1})**	**Soil CN ratio**	**Soil pH**	**Residual soil mineral N (mg kg^{-1})**	**Soil CN ratio**
Amendment (AM)						
LIME	6.0ab	43.5a	26.0	6.5a	20.3a	19b
WA	6.2a	21.8c	26.3	6.3ab	3.3b	21b
SL	5.6c	27.7b	28.8	6.2b	2.2c	27a
WASL	6.0ab	12.4d	27.5	6.3ab	2.1c	20b
Biochar (BC)						
0 Mg ha^{-1}	5.9	28.3a	24.2b	6.2	5.7b	20b
20 Mg ha^{-1}	5.9	24.4b	30.0a	6.3	8.4a	22a
			***p*-value**			
AM	<0.001	<0.001	0.12	0.01	<0.001	<0.001
BC	1.00	<0.001	<0.001	0.08	<0.001	0.02
AM × BC	0.92	<0.001	0.21	0.53	<0.001	0.39

Note: Letters denoting pairwise comparisons in the table represents the reuslts of LSD tests. Different letters signify statistically significant differnces at $p < 0.05$.
Abbreviations: LIME, limestone; SL, paper sludge; WA, wood ash; WASL, WA + SL.

LIME and WASL. Overall, residual soil mineral N varied in the order LIME = SL > WA > WASL without BC and LIME > WA > SL = WASL when BC was added. In both experiments, WA and WASL significantly reduced residual soil mineral N, regardless of BC level. In Experiment 2, there were no significant differences among the paper mill waste treatments, and they all had lower residual soil mineral N than LIME at both BC levels (Figure 3).

In Experiment 1, combining BC with AMs significantly increased soil CN ratio at the time of harvest (Table 4). Conversely, soil CN ratios did not significantly vary among AMs. For Experiment 2, there were significant AM and BC effects on soil CN ratio. Soil amended with SL had significantly higher CN ratio than with LIME, WA, and WASL. Regardless of AM, BC addition increased soil CN ratio compared to liming alone.

4 | DISCUSSION

4.1 | Plant N uptake and yield

Greater N uptake was observed in WA and WASL (80% WA and 20% SL) than in LIME and SL in both experiments. Higher N uptake in WA treatment might be possible due to the presence of high K^+ that is 177% more than SL (Table 1). K^+ plays an important role in maintaining proper water balance by influencing the closing and opening of the leaf stomata, and it helps to regulate osmotic potential that affects water movement within plant issues. Therefore, in case of sufficient K^+ levels, it helps to maintain proper water potential, which indirectly supports movements of nitrate ions within the plant through xylem tissues (Sardans & Peñuelas, 2021). Enhanced N uptake in WA may also be due to the alkaline conditions created by WA, which result in greater availability of NO_3^- (Table 1) (Neina, 2019; Pugliese et al., 2014). These results are in agreement with the findings of Brod et al. (2012), who reported that WA mixed with inorganic fertilizer increased N uptake in *Lolium perenne* L. Couch et al. (2020) reported that application of WA increases mineralization of C and N via microbial respiration, resulting in more N availability for plants. WA application along with N fertilizer enhanced N uptake in *Pinus sylvestris* and reduced residual N (NH_4^+ and NO_3^-) in soil (Saarsalmi et al., 2014).

Lower N uptake was observed in SL treatments without BC addition (Table 3). These results agree with those reported by Sippola et al. (2003) who observed lower N in plants amended with SL compared to plants fertilized with inorganic N fertilizer. Lower uptake in SL might be due to its high CN ratio (38.6) more than the double compared to WA (16.7) (Table 1). The higher CN ratio of the SL might have immobilized N by microbial activity and reduced overall N uptake in shoots (Tables 3 and 4). Interestingly, in both experiments, BC addition increased CN ratio and reduced overall N uptake, this could be due to higher CN ratio of BC, as it is primarily composed of recalcitrant carbon and has relatively lower N, that might have increased overall CN ratio when combined with paper mill amendments (Tables 3 and 4). This observation is in line with Alburquerque et al. (2013), who reported that BC addition decreased N uptake in *Triticum aestivum* and could be possible due to high CN ratio of BC. Zhang et al. (2014) reported that BC application increased soil microbial activity that led to increase in CN ratio. Deenik et al. (2010) reported that BC contains volatile fractions that can be readily degradable and may increase CN ratio in soil.

In the present studies WA, SL, and WASL produced 52%, 31%, and 41% higher biomass (Experiment 1), 74%, 57%, and 74% (Experiment 2) of annual ryegrass as compared to LIME, respectively (Table 3). These results corroborate the findings of Ziadi et al. (2013), who reported that the application of paper mill biosolids increased shoot biomass of *Hordeum vulgare* L. and increased plant N, P, and Ca uptake. Similar findings of increased plant growth and biomass due to WA application were reported by Bonfim-Silva et al. (2017), where WA addition increased shoot biomass of *Brachiaria brizantha* (cv. BRS Piatã) by 94% compared to treatments that contained lower rates of WA fertilization. Higher biomass in mill amendments could be attributed to the presence of essential nutrients, for example, Ca, Mg, K, Mo, Fe, and Zn, that facilitated annual ryegrass growth by activating various enzymes and stabilizing plant metabolism, for example, osmoregulation and protein synthesis processes, resulting in higher plant height and biomass (Hasanuzzaman et al., 2018; Wu et al., 2018; Sikder et al., 2020).

In addition, the higher biomass yield in Experiment 2 than in Experiment 1 (Table 3) could be due to several reasons, some possibilities including Experiment 2 soil was higher in calcium, potassium, and organic matter, plus this experiment was conducted in summer season with higher average temperature, light intensity, and humidity (Figure 2). These two experiments were conducted in different seasons (Winter 2019 and Summer 2020); however, the trend of paper mill amendments in comparison with traditional practice of LIME application is the same with respect to liming, growth, and crop yield.

4.2 | Soil pH and residual soil nitrogen

WA and SL are the potential alternate liming materials that can be substituted with commercial LIME. In Experiment 1, we observed increased soil pH with WA and WASL (80% WA + 20% SL) in combination with SL than alone (Table 4). The increase in soil pH treated with WA and WASL compared to SL might be due to the presence of high exchangeable Ca in WA, which is 433% higher than SL (Table 1). The substantial influence of WA on soil chemistry exhibits a similarity to the effects observed with liming, emphasizing the crucial role of calcium in influencing this process (Kim et al., 2022). In addition, the small particle size of WA might have initiated a more pronounced reaction with the soil, causing a more rapid alteration in pH compared to SL. These results are in line with the study conducted by Sharifi et al. (2013), in which WA was more efficient in increasing soil pH considering its high alkalinity (pH 12) and superior water solubility compared to other liming sources. The lower liming potential of SL might be due to its lower pH and large particle size (Table 1; Chantigny et al., 2000). In Experiment 2, we observed that WA and SL alone and in combination with BC increased soil pH from 5.2 to a target pH of 6.2–6.3. These results corroborate findings from other studies that reported that the application of paper mill biosolids alone and in combination with BC increased

soil pH to a greater extent than commercial LIME (Adotey et al., 2018; Manirakiza et al., 2019).

In both experiments, WA was more efficient in increasing soil pH. This observation can be attributed to the presence of carbonates, oxides, and hydroxides (Kapembwa et al., 2020; Neina, 2019) and smaller particle size, which provides a greater surface area for reactions (Hu et al., 2020). These findings are similar to the studies reported by Adotey et al. (2018), who observed increased soil pH with WA application compared to commercial LIME. Although, in Experiment 1, SL did not perform well compared to Experiment 2, where SL application successfully attained the target soil pH (6.3). This might be due to the increased application of SL in Experiment 2, which could have increased the overall exchangeable calcium amount and provided more time (reapplication of amendments due to COVID-19) for the large SL particles to decompose and react with soil.

In Experiment 1, BC-amended WA and WASL exhibited higher residual N (Figure 3). This might be due to the high CN ratio of BC that leads to immobilization of N in WA-amended treatments. Additionally, BC has a high surface area, which can retain nutrients, including N, that can directly influence the availability and release of N from amendments (Jeffery et al., 2011). Contrary to WA, BC-amended SL showed lower residual N; this could be the result of immobilization (biological fixation by microbes) or N mineralization in sludge that was not synchronized with crop needs over time (Luo et al., 2018; Sippola et al., 2003).

4.3 | Conclusion and recommendations

The results suggest significant potential of WA as an alternative amendment for liming and yield improvement of annual ryegrass grown in NL podzolic soils. On the other hand, SL may have limited potential due to the risk of increasing N immobilization and residual soil mineral N when growing conditions are limiting. Combining SL with WA or BC seemed to alleviate these risks. The adoption of these amendments for field production systems warrants serious consideration in NL and other regions with similar soils or challenges. However, the current study only provides evidence that these materials are worth considering for large-scale adoption and requires supplemental field studies to determine optimal application rates and timing before recommendations can be made. These materials are also prone to variability in contaminant levels, so it is important to take additional precautions, such as combining them with BC.

AUTHOR CONTRIBUTIONS

Bilal Javed: Conceptualization; data curation; formal analysis; methodology; software; validation; visualization; writing—original draft; writing—review and editing. **Yeukai Katanda**: Conceptualization; data curation; formal analysis; methodology; project administration; resources; software; validation; visualization; writing—review and editing. **Muhammad Nadeem**: Methodology; software; supervision; validation; visualization; writing—review and editing. **Muhammad Farhain**: Data curation; writing—review and editing. **Thilini Wickremasinghe**: Data curation; formal analysis; writing—review and editing. **Raymond Thomas**: Supervision; validation; visualization; writing—review and editing. **Lakshman Galagedara**: Project administration; resources; supervision; validation; visualization; writing—review and editing. **Xiaobin Guo**: Conceptualization; resources; validation; writing—review and editing. **Mumtaz Cheema**: Conceptualization; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; visualization; writing—review and editing.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ORCID

Bilal Javed https://orcid.org/0009-0009-5450-833X

REFERENCES

Abbasi, M. K., Afsar, N., & Rahim, N. (2013). Effect of wood ash and compost application on nitrogen transformations and availability in soil-plant systems. *Soil Science Society of America Journal*, *77*(2), 558–567. https://doi.org/10.2136/sssaj2012.0365

Adotey, N., Harrell, D. L., & Weatherford, W. P. (2018). Characterization and liming effect of wood ash generated from a biomass-fueled commercial power plant. *Communications in Soil Science and Plant Analysis*, *49*(1), 38–49. https://doi.org/10.1080/00103624.2017.1421643

Alburquerque, J. A., Salazar, P., Barrón, V., Torrent, J., Del Campillo, M. D. C., Gallardo, A., & Villar, R. (2013). Enhanced wheat yield by biochar addition under different mineral fertilization levels. *Agronomy for Sustainable Development*, *33*(3), 475–484. https://doi.org/10.1007/s13593-012-0128-3

Barrett, J., & Vodden, K. (2023). Partnerships in place: Facilitating rural local government entrepreneurialism in Newfoundland and Labrador. *Canadian Geographies*, *67*, 188–197. https://doi.org/10.1111/cag.12814

Bertsch, F., & Ostinelli, M. (2019). *Standard operating procedure for soil total carbon: Dumas dry combustion method*. FAO.

Bonfim-Silva, E. M., Pereira, M. T. J., Da Silva, T. J. A., & Fenner, W. (2017). Potential of wood ash as a fertilizer in BRS Piatã grass cultivation in the Brazilian Cerrado soil. *American Journal of Plant Sciences*, *8*(10), 2333–2344. https://doi.org/10.4236/ajps.2017.810156

Brod, E., Haraldsen, T. K., & Breland, T. A. (2012). Fertilization effects of organic waste resources and bottom wood ash: Results from a pot experiment. *Agricultural and Food Science*, *21*(4), 332–347. https://doi.org/10.23986/afsci.5159

Cairns, S., Robertson, I., Holliman, P., & Street-Perrott, A. (2022). Treatments of wood ash amended biochar to reduce nutrient leaching

and immobilise lead, copper, zinc and cadmium in aqueous solution: Column experiments. *Environmental Science: Water Research & Technology*, *8*, 1277–1286.

Camberato, J., Gagnon, B., Angers, D., Chantigny, M., & Pan, W. (2006). Pulp and paper mill by-products as soil amendments and plant nutrient sources. *Canadian Journal of Soil Science*, *86*, 641–653.

Canadian Council of Ministers of the Environment. (2012). *Guidelines for the Use of biosolids in agriculture and reclamation*. Canadian Council of Ministers of the Environment.

Chantigny, M. H., Angers, D. A., & Beauchamp, C. J. (2000). Decomposition of de-inking paper sludge in agricultural soils as characterized by carbohydrate analysis. *Soil Biology and Biochemistry*, *32*(11–12), 1561–1570.

Cherian, C., & Siddiqua, S. (2019). Pulp and paper mill fly ash: A review. *Sustainability*, *11*(16), 4394. https://doi.org/10.3390/su11164394

Couch, R. L., Luckai, N., Morris, D., & Diochon, A. (2020). Short-term effects of wood ash application on soil properties, growth, and foliar nutrition of *Picea mariana* and *Picea glauca* seedlings in a plantation trial. *Canadian Journal of Soil Science*, *101*, 203–215. https://doi.org/10.1139/cjss-2020-0105

Cruz, N., Avellan, A., Ruivo, L., Silva, F. C., Römkens, P. F. A. M., Tarelho, L. A. C., & Rodrigues, S. M. (2023). Biomass ash-based soil improvers: Impact of formulation and stabilization conditions on materials' properties. *Journal of Cleaner Production*, *391*, 136049. https://doi.org/10.1016/j.jclepro.2023.136049

Deenik, J. L., McClellan, T., Uehara, G., Antal, M. J., & Campbell, S. (2010). Charcoal volatile matter content influences plant growth and soil nitrogen transformations. *Soil Science Society of America Journal*, *74*(4), 1259–1270. https://doi.org/10.2136/sssaj2009.0115

Elkhlifi, Z., Iftikhar, J., Sarraf, M., Ali, B., Saleem, M. H., Ibranshahib, I., Bispo, M. D., Meili, L., Ercisli, S., & Torun Kayabasi, E. (2023). Potential role of biochar on capturing soil nutrients, carbon sequestration and managing environmental challenges: A review. *Sustainability*, *15*, 2527.

Farhain, M. M., Cheema, M., Katanda, Y., Nadeem, M., Javed, B., Thomas, R., & Galagedara, L. (2022). Potential of developing podzolic soil-based potting media from wood ash, paper sludge and biochar. *Journal of Environmental Management*, *301*, 113811.

Gagnon, B., & Ziadi, N. (2023). Paper mill biosolids and forest-derived liming materials applied on cropland: residual effects on soil properties and metal availability. *Soil Systems*, *7*, 40.

Hajiboland, R., Panda, C. K., Lastochkina, O., Gavassi, M. A., Habermann, G., & Pereira, J. F. (2023). Aluminum toxicity in plants: Present and future. *Journal of Plant Growth Regulation*, *42*, 3967–3999. https://doi.org/10.1007/s00344-022-10866-0

Hanson, J. L., Manheim, D. C., & Yeşiller, N. (2023). Geoenvironmental assessment of climate impacts from landfill gas emissions. *Soils and Foundations*, *63*, 101279. https://doi.org/10.1016/j.sandf.2023.101279

Hasanuzzaman, M., Bhuyan, M. H. M. B., Nahar, K., Hossain, M. S., Al Mahmud, J., Hossen, M. S., Masud, A. A. C., Moumita, & Fujita, M. (2018). Potassium: A vital regulator of plant responses and tolerance to abiotic stresses. *Agronomy*, *8*(3), 31. https://doi.org/10.3390/agronomy8030031

Hendershot, W. H., Lalande, H., & Duquette, M. (1993). Soil reaction and exchangeable acidity. In M. R. Carter & E. G. Gregorich (Eds.), *Soil sampling and methods of analysis* (2nd ed.). CRC Press.

Hu, X., Jarnerud, T., & Karasev, A. (2020). Utilization of fly ash and waste lime from pulp and paper mills in the Argon Oxygen Decarburization process. *Journal of Cleaner Production*, *261*, 121182. https://doi.org/10.1016/j.jclepro.2020.121182

Jeffery, S., Verheijen, F. G., van der Velde, M., & Bastos, A. C. (2011). A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture, Ecosystems & Environment*, *144*(1), 175–187.

Kapembwa, C., Shitumbanuma, V., Chabu, K., & Van Ranst, E. (2020). Evaluation of the effectiveness of a new method of measuring the chemical reactivity of liming materials on two acid soils from Zambia. *Communications in Soil Science and Plant Analysis*, *51*(3), 327–340. https://doi.org/10.1080/00103624.2019.1705324

Kar, G., Kumar, A., Sahoo, N., & Singh, R. (2014). Use of paper mill sludge as an alternative liming material and its impacts on light interception radiation utilization efficiency of groundnut in acid soils of eastern India. *Journal of Agricultural Physics*, *14*(1), 10–21.

Katanda, Y. (2022). *Interseeded cover crops in Ontario grain corn systems: Potential implications for corn nitrogen uptake, soil health, and residue decomposition*. Trent University.

Kedir, A. J., Zhang, M., & Unc, A. (2021). Understanding soil fertility status in Newfoundland from standard farm soil tests. *Canadian Journal of Soil Science*, *101*, 517–531. https://doi.org/10.1139/cjss-2020-0108

Kim, N., Watmough, S. A., & Yan, N. D. (2022). Wood ash amendments as a potential solution to widespread calcium decline in eastern Canadian forests. *Environmental Reviews*, *30*, 485–500.

Kinnula, S., Toivonen, M., Soinne, H., Joona, J., & Kivelä, J. (2020). Effects of mixed pulp mill sludges on crop yields and quality. *Agricultural and Food Science*, *29*(4), 276–286. https://doi.org/10.23986/afsci.95600

Kopittke, P. M., Moore, K. L., Lombi, E., Gianoncelli, A., Ferguson, B. J., Blamey, F. P. C., Menzies, N. W., Nicholson, T. M., McKenna, B. A., Wang, P., Gresshoff, P. M., Kourousias, G., Webb, R. I., Green, K., & Tollenaere, A. (2015). Identification of the primary lesion of toxic aluminum in plant roots. *Plant Physiology*, *167*(4), 1402–1411. https://doi.org/10.1104/pp.114.253229

Likon, M., & Trebe, P. (2012). Recent advances in paper mill sludge management. In K.-Y. Show & X. Guo (Eds.), *Industrial waste* (pp. 73–90). IntechOpen. https://doi.org/10.5772/37043

Linn, D. M., & Doran, J. W. (1984). Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils. *Soil Science Society of America Journal*, *48*, 1267–1272. https://doi.org/10.2136/sssaj1984.03615995004800060013x

Luo, G., Li, L., Friman, V. P., Guo, J., Guo, S., Shen, Q., & Ling, N. (2018). Organic amendments increase crop yields by improving microbe-mediated soil functioning of agroecosystems: A meta-analysis. *Soil Biology and Biochemistry*, *124*, 105–115. https://doi.org/10.1016/j.soilbio.2018.06.002

Manirakiza, E., Ziadi, N., Luce, M. S., Hamel, C., Antoun, H., & Karam, A. (2019). Nitrogen mineralization and microbial biomass carbon and nitrogen in response to co-application of biochar and paper mill biosolids. *Applied Soil Ecology*, *142*, 90–98.

Maynard, D. G., & Kalra, Y. P. (2008). *Soil science: Methods & applications*. Taylor & Francis.

Medaiyese, A. O., Wu, J., & Unc, A. (2023). Utility of wood ash, paper sludge and biochar for the mitigation of greenhouse gases emissions from acid boreal soils. *Journal of Environmental Management*, *330*, 117202. https://doi.org/10.1016/j.jenvman.2022.117202

Moragues-Saitua, L., Arias-González, A., & Gartzia-Bengoetxea, N. (2017). Effects of biochar and wood ash on soil hydraulic properties:

A field experiment involving contrasting temperate soils. *Geoderma*, *305*, 144–152.

Mosa, A., Mansour, M. M., Soliman, E., El-Ghamry, A., El Alfy, M., & El Kenawy, A. M. (2023). Biochar as a soil amendment for restraining greenhouse gases emission and improving soil carbon sink: Current situation and ways forward. *Sustainability*, *15*(2), 1206.

Muse, J. K., & Mitchell, C. C. (1995). Paper mill boiler ash and lime by-products as soil liming materials. *Agronomy Journal*, *87*, 432–438. https://doi.org/10.2134/agronj1995.00021962008700030008x

Neina, D. (2019). The role of soil pH in plant nutrition and soil remediation. *Applied and Environmental Soil Science*, *2019*(3), 5794869. https://doi.org/10.1155/2019/5794869

Norrie, J., & Fierro, A. (2020). Paper sludges as soil conditioners. In A. Wallace & R. E. Terry (Eds.), *Handbook of soil conditioners* (pp. 97–115). CRC Press.

Ochecova, P., Tlustos, P., & Szakova, J. (2014). Wheat and soil response to wood fly ash application in contaminated soils. *Agronomy Journal*, *106*(3), 995–1002. https://doi.org/10.2134/agronj13.0363

Paramisparam, P., Ahmed, O. H., Omar, L., Ch'ng, H. Y., Johan, P. D., & Hamidi, N. H. (2021). Co-application of charcoal and wood ash to improve potassium availability in tropical mineral acid soils. *Agronomy*, *11*(10), 2081.

Park, N. D., Rutherford, M. P., Thring, R. W., & Helle, S. S. (2012). Wood pellet fly ash and bottom ash as an effective liming agent and nutrient source for rye grass (*Lolium perenne* L.) and oats (*Avena sativa*). *Chemosphere*, *86*(4), 427–432. https://doi.org/10.1016/j.chemosphere.2011.10.052

Pazalja, M., Salihović, M., Sulejmanović, J., Smajović, A., Begić, S., Špirtović-Halilović, S., & Sher, F. (2021). Heavy metals content in ashes of wood pellets and the health risk assessment related to their presence in the environment. *Scientific Reports*, *11*(1), 17952.

Pugliese, S., Jones, T., Preston, M. D., Hazlett, P., Tran, H., & Basiliko, N. (2014). Wood ash as a forest soil amendment: The role of boiler and soil type on soil property response. *Canadian Journal of Soil Science*, *94*(5), 621–634. https://doi.org/10.4141/cjss-2014-037

Quaye, A. K., Volk, T. A., Hafner, S., Leopold, D. J., & Schirmer, C. (2011). Impacts of paper sludge and manure on soil and biomass production of willow. *Biomass and Bioenergy*, *35*, 2796–2806.

Ríos, D., Pérez, C., & Sandoval, M. (2012). Phytotoxic effect of paper pulp sludge on Alfisol soil. *Journal of Soil Science and Plant Nutrition*, *12*(2), 315–327.

Rodríguez, Y., Maudier, B., Zagal, E., & Hernández, P. (2019). Effects of wood ash on nutrients and heavy metal(oid)s mobility in an Ultisol. *International Journal of Environmental Research and Public Health*, *16*(7), 1246.

Royer-Tardif, S., Whalen, J., & Rivest, D. (2019). Can alkaline residuals from the pulp and paper industry neutralize acidity in forest soils without increasing greenhouse gas emissions? *Science of the Total Environment*, *663*, 537–547. https://doi.org/10.1016/j.scitotenv.2019.01.337

Saarsalmi, A., Smolander, A., Moilanen, M., & Kukkola, M. (2014). Wood ash in boreal, low-productive pine stands on upland and peatland sites: Long-term effects on stand growth and soil properties. *Forest Ecology and Management*, *327*, 86–95. https://doi.org/10.1016/j.foreco.2014.04.031

Saha, R., Galagedara, L., Thomas, R., Nadeem, M., & Hawboldt, K. (2020). Investigating the influence of biochar amendment on the physicochemical properties of podzolic soil. *Agriculture*, *10*, 471.

Sardans, J., & Peñuelas, J. (2021). Potassium control of plant functions: Ecological and agricultural implications. *Plants*, *10*(2), 419.

Sharifi, M., Cheema, M., McVicar, K., LeBlanc, L., & Fillmore, S. (2013). Evaluation of liming properties and potassium bioavailability of three Atlantic Canada wood ash sources. *Canadian Journal of Plant Science*, *93*(6), 1209–1216. https://doi.org/10.4141/CJPS2013-168

Sikder, R. K., Wang, X., Zhang, H., Gui, H., Dong, Q., Jin, D., & Song, M. (2020). Nitrogen enhances salt tolerance by modulating the antioxidant defense system and osmoregulation substance content in *Gossypium hirsutum*. *Plants*, *9*(4), 450. https://doi.org/10.3390/plants9040450

Simão, L., Hotza, D., Raupp-Pereira, F., Labrincha, J. A., & Montedo, O. R. K. (2018). Wastes from pulp and paper mills—A review of generation and recycling alternatives. *Ceramica*, *64*(371), 443–453. https://doi.org/10.1590/0366-69132018643712414

Simard, R. R. (1993). Ammonium acetate-extractable elements. In M. R. Carter & E. G. Gregorich (Eds.), *Soil sampling and methods of analysis* (pp. 39–42). Lewis Publishers.

Sippola, J., Mäkelä-Kurtto, R., & Rantala, P. R. (2003). Effects of composted pulp and paper industry wastewater treatment residuals on soil properties and cereal yield. *Compost Science and Utilization*, *11*(3), 228–237. https://doi.org/10.1080/1065657X.2003.10702131

USEPA. (1993). *Method 353.2: Methods for the determination of inorganic substances in environmental samples* (USEPA 600/R93/100). USEPA.

Wu, H., Zhang, X., Giraldo, J. P., & Shabala, S. (2018). It is not all about sodium: revealing tissue specificity and signalling roles of potassium in plant responses to salt stress. *Plant and Soil*, *431*(1–2), 1–17. https://doi.org/10.1007/s11104-018-3770-y

Yamamoto, Y. (2019). Aluminum toxicity in plant cells: Mechanisms of cell death and inhibition of cell elongation. *Soil Science and Plant Nutrition*, *65*(1), 41–55. https://doi.org/10.1080/00380768.2018.1553484

Yang, R., Mitchell, C. C., & Howe, J. A. (2018). Relative neutralizing value as an indicator of actual liming ability of limestone and byproduct materials. *Communications in Soil Science and Plant Analysis*, *49*(10), 1144–1156. https://doi.org/10.1080/00103624.2018.1448866

Zhang, Q.-Z., Dijkstra, F. A., Liu, X.-R., Wang, Y.-D., Huang, J., & Lu, N. (2014). Effects of biochar on soil microbial biomass after four years of consecutive application in the north China Plain. *PLoS ONE*, *9*, e102062.

Zheng, S. J. (2010). Crop production on acidic soils: Overcoming aluminium toxicity and phosphorus deficiency. *Annals of Botany*, *106*(1), 183–184. https://doi.org/10.1093/aob/mcq134

Ziadi, N., Gagnon, B., & Nyiraneza, J. (2013). Crop yield and soil fertility as affected by papermill biosolids and liming by-products. *Canadian Journal of Soil Science*, *93*(3), 319–328. https://doi.org/10.4141/CJSS2012-129

How to cite this article: Javed, B., Katanda, Y., Nadeem, M., Wickremasinghe, T., Farhain, M. M., Thomas, R., Galagedara, L., Guo, X., & Cheema, M. (2024). Effectiveness of wood ash and paper sludge as liming and nutrient sources for annual ryegrass grown in podzolic soils of Newfoundland. *Soil Science Society of America Journal*, *88*, 792–802. https://doi.org/10.1002/saj2.20648